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Research Paper

Towards a low-carbon Mexican chemical industry

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HIGHLIGHTS

- A BAU and a low carbon scenarios are constructed in MCI's energy end-use terms.
- The implementation of 15 mitigation measures of greenhouse gases is analyzed.
- 10 efficient energy measures and 5 renewable energy technologies are considered.
- The proposed low carbon scenario generates a net economic benefit of $7.2 billion.
- The low carbon scenario reduces 65% the cumulative GHG emissions from BAU scenario.

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ABSTRACT

In 2014, the Mexican Chemical Industry (MCI) energy consumption represented 13.5% of the industrial sector total consumption (211 PJ), being the industry with the second highest greenhouse gases (GHG) emissions in Mexico with 13.8 $MtCO_{2e}$. This article shows that in the medium and long term it is feasible to transform the MCI into a low-carbon industry. To prove this hypothesis, two scenarios are constructed in terms of the MCI's final energy uses: a business as usual (BAU) scenario and an alternative one, a low-carbon scenario which analyzes 15 GHG mitigation measures, 10 related to efficient energy use (EEU) and 5 associated with the implementation of renewable energy sources (RES). The results show that, when compared to the BAU scenario, the low-carbon scenario reduces the MCI's energy consumption by 63.5% in 2030 and by 78.5% in 2050, resulting in a cumulative total GHG emissions reduction of 65%. Additionally, the low-carbon scenario will not generate costs in the analyzed period; on the contrary, it would produce a global economic benefit above 7200 million USD (MUSD). Likewise, the results show that the implementation of this alternative scenario requires an incremental investment over 377 MUSD/year within the analysis period. Finally, implementing the proposed low-carbon scenario results in a significant modification of the MCI energy end-use structure.

1. Introduction

The chemical industry is a complex industry that covers a large number of processes, ranging from continuous processes to produce basic chemicals to large volumes of batch processes to produce specialty chemicals and pharmaceutical ingredients. Chemicals are used in a wide variety of final consumer products, playing an important role in the global economy, for example in the European Union, more than 140,000 chemicals are registered for marketing and expects that about 30,000 new substances will be registered in 2018 [1]. The chemical industry is one of the world's largest industry with a 7% share of world GDP and global sales of 4,730 billion[1] USD [2]. This is reflected both in its energy consumption and in its generation of GHG emissions. Indeed, in 2012 the energy consumption of the global chemical industry was 15 EJ, representing 10% of the final consumption of world energy, which shows the energy intensive nature of its production processes, which

Abbreviations: AV, added value; BAU, business as usual; CHP, combined heat and power; COP21, twenty-first meeting of the Conference of the Parties of the United Nations Framework Convention on Climate Change; E, electricity; EEU, efficient energy use; EJ, Exajoule; EU, European Union; FF, fossil fuels; GDP, gross domestic product; GHG, greenhouse gases; NG, natural gas; GWP, global warming potential; IC, investment cost; kWh, kilo-watt hour; LC, low carbon; LPG, liquefied petroleum gas; MCI, Mexican chemical industry; $MtCO_{2e}$, million ton of equivalent carbon dioxide; MUSD, millions of U.S. dollars; NC, net cost; NDC, nationally determined contribution; O&M, operation and maintenance; PJ, petajoule; RES, renewable energy sources; SEN, national electric system; USD, United States dollars

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[1] Monetary amounts are expressed in constant US dollars for 2007.

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require high temperatures and in consequence, they generate significant GHG emissions, mainly due to fossil fuels (FF) burning for process heat generation used in their production processes. In this way the global chemical industry is responsible for generating 7% of global GHG emissions [3]. Therefore, it is important to analyze and propose mitigation measures to move towards a global low carbon chemical industry. For example, global studies show that in the European Union (EU) since 1990 the chemical industry has reduced its GHG emissions by 59% as a result of a gradual decoupling between its energy consumption and its production and is planning a reduction of 89% by 2050 [4,5]. Also in the United Kingdom (UK) it is anticipated that its chemical industry will reduce its GHG emissions by 90% by the same year [6]. In both cases, these reductions are achieved through the implementation of various GHG mitigation measures, such as combined heat and power (CHP), process integration and the use of low-carbon electricity.

The Mexican chemical industry (MCI) is no exception to this climate problem generated by the world chemical industry. In fact, the MCI consumed 211 PJ in 2014, which represented 13.5% of the total consumption of the Mexican industrial sector, which places it as the second most energy intensive industry in Mexico. Where 88% of its consumption corresponds to the use of FF, where natural gas (NG) is the most used fuel with 84% (156 PJ) of total consumption, while 12% (25 PJ) was electricity (E) and the remaining 4% belongs to the consumption of diesel (2.3%), petroleum coke (0.3%), fuel oil (1%) and liquefied petroleum gas (LPG) (0.4%) [7], see Fig. 1.

Due to these consumptions the MCI emitted a total of 13.8 $MtCO_{2e}$, which considers the indirect emissions from the consumption of electricity. These emissions account for just over 9% of global emissions from the Mexican industrial sector [8]. GHG mitigation in this industry represents a challenge for Mexico to meet its mitigation commitments, called Intended Nationally Determined Contributions (INDCs) that are part of the Paris COP21 agreement, in which Mexico commits itself to reduce their emissions by 22% unconditionally by 2030 and by 36% on a conditional basis [9]. Consequently, if Mexico is looking for a route to meet its international commitments on GHG mitigation, the MCI should be decarbonized. To achieve this, a technical and economic feasibility study of a low carbon scenario for the MCI based on 15 measures of GHG mitigation, 10 related to the efficient use of energy (EEU) and 5 to the use of renewable energy sources (RES) is presented. To prove this feasibility, two scenarios, a BAU scenario and a low carbon scenario were constructed, both in terms of MCI's final energy uses, and a net cost analysis of these scenarios was carried out.

1.1. The current situation of the Mexican chemical industry

The MCI is one of the main economic activities of the country. In 2014, this industry generated an added value (AV) of approximately $18,600 MUSD, which represented 1.8% of the national GDP, 11.8% of the industrial sector AV in Mexico with 150,000 employees in 583 companies [10]. According to a study carried out by the United Nations Development Program (UNDP) in conjunction with the National Chemical Industry Association (ANIQ) [11], it is expected that one of the main effects of the recent energy reform in Mexico, in the medium and long term, will be the reduction of the MCI imports. According to this study, this reduction will allow a greater self-sufficiency of raw material that will promote the growth of its AV, since we assume a substitution of 25% of imports, which would have consequently a MCI's AV growth at an annual average rate of 3.9% between 2014 and 2050 instead of the forecasted 2.1% before this reform. This higher growth rate is in line with the MCI growth forecasts estimated by various international organizations [1,2,12]. Taking as reference studies on final energy consumption in the chemical industry [13,14] and official data [7,15], it can be estimated that currently in the end-use energy structure of the MCI, 94% of FF is burned in boilers to produce steam, the remaining 6% is used in thermal fluid boilers (4%) and in furnaces & dryers (2%). Electricity is consumed mainly by electric motors, which represents 73% of its total consumption, distributed in compressed air (20%), pumping (19%), ventilation (9%), refrigeration (6%) and others 19%). The remaining 27% of electricity consumption is in illumination (17%) and other uses (10%), see Fig. 2.

Fig. 3 shows the GHG emissions by energy end-use. This structure confirms that the largest amount of emissions, 76.5% of the MCI, is generated due to FF burning in boilers for steam production, heating of thermal fluids, furnaces and dryers. Electricity consumption implies 17.5% used mainly for electric motors and the remaining 6% for lighting and diverse uses. From this structure, it is demonstrated that this industry is intensive in emissions, so this article will analyze various mitigation measures of GHG by energy end use to achieve a low carbon MCI.

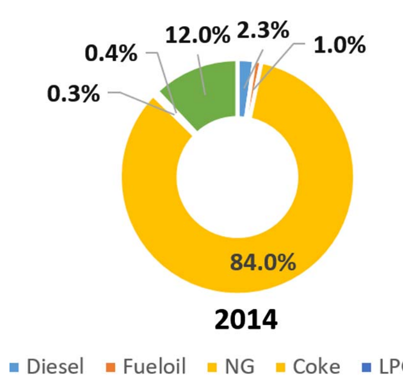

Fig. 1. Mexican Chemical Industry energy consumption structure in 2014.. Source: [7]

2. General methodology

This study was carried out with the following method:

- First, the year 2014 is established as the reference year to construct the BAU and LC scenarios, which is the most recent year where there is available and complete, data to represent in detail the consumption of energy by MCI's end-uses.
- Secondly, a BAU scenario is constructed, considering the growth forecast for the MCI's AV [12] and the increase in energy consumption and in GHG emissions by MCI's energy end-uses is projected for the period 2015–2050.
- Third, to build a low carbon (LC) scenario, a portfolio of viable GHG mitigation measures based on efficient use of energy and in the use of renewable energy sources is developed.
- Fourth, the penetration level of each GHG mitigation measure considered for the LC scenario in the period of analysis was determined based on expert opinion obtained using the Delphi technique.
- Finally, a net cost (NC) analysis of the GHG mitigation measures of the LC scenario is carried out. Due to the fact that this article intends to carry out a conservative economic analysis, it is considered as an important work hypothesis to keep the costs of investment, O&M and fuels, constant and equal to the current ones. It is also part of the working hypothesis to consider only the direct costs in these areas.

2.1. BAU scenario

Once the energy end-use structure for the reference year is established (Fig. 2), the BAU scenario for the period 2015–2050 is calculated by projecting the energy consumption by energy end-use, taking as a guideline variable the growth of the MCI's AV established by [11] where, as already mentioned, the MCI AV grows at an average annual rate of 3.9% between 2014 and 2050. Table 1 shows the unit costs of

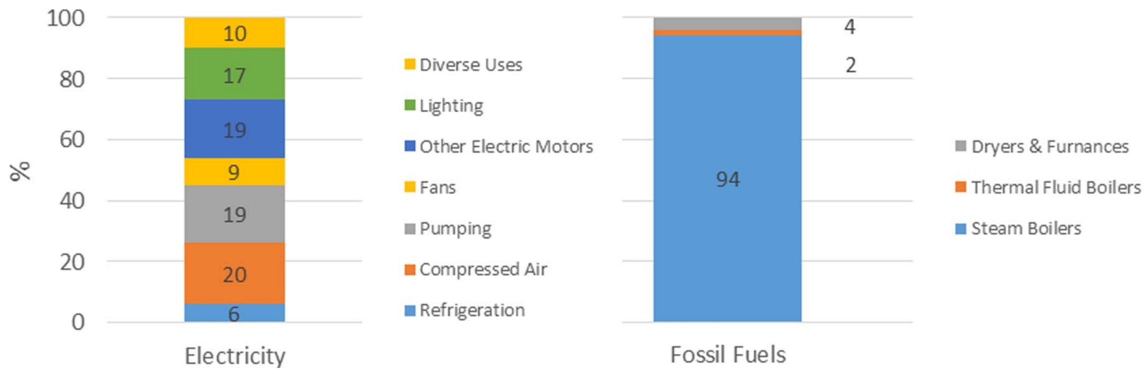

Fig. 2. End Uses of Energy in the MCI 2014..
Source: Own data based on [7,13–15]

investment and O&M in present value for the whole period by energy end-uses of the MCI. The unit cost of energy is represented by the unit costs of E and FF; these costs are included in the O&M costs and according to the reference [26] are the following: electricity (29.5 USD/GJ) (0.11 USD/kWh), diesel (23.9 USD/GJ), fuel oil (11.3 USD/GJ), NG (3.4 USD/GJ), LPG (19 USD/GJ) and Coke (0.33 USD/GJ). With this information, we proceeded to estimate a unit-weighted average cost of fossil fuels where the percentage of weighting corresponds to the structure of final consumption of fossil fuels in the MCI and is as follows based on Fig. 1, diesel (2.5%), fuel oil (1.1%), NG (95.6%), LPG (0.3%) and Coke (0.5%). The value obtained is 4.3 USD/GJ and is used in this article to represent the average annual cost of fossil fuels consumed in the different end uses of energy in the MCI.

The direct GHG emissions from this scenario were determined using the emission factors and the global warming potential of the IPCC [63,64] for each FF used for the energy end-uses that require thermal energy. While indirect emissions, derived from electricity consumption, were calculated using the average emission factor for Mexico's national electricity system, with a value of 0.454 $kgCO_{2e}$/kWh [65], assuming no changes in the structure of inputs used for electricity production in the analyzed period.

2.2. Low-carbon scenario

The LC scenario was constructed as follows:

- First, the reduction potential in the consumption of E and in the use of FF of 10 mitigation measures based on EEU and 5 measures based on the use of RES were determined. Table 2 presents the description of the 15 GHG mitigation measures considered in this article and their respective investment and O&M unit costs, including in the latter the unit costs of energy. Table 3 shows, in percentage terms, the breakdown of this reduction potential according to the energy end-uses of the MCI that are affected by the mitigation measures. While Table 4 shows the breakdown of the unit costs of the mitigation measures by energy end-uses.
- Second, the GHG mitigation potential of the portfolio of 15 mitigation measures, is calculated from energy consumption reduction

Table 1
Total BAU unit costs by energy final use, 2015–2050.
Source: Own calculations based on the cited references.

Energy final use	Unit costs (MUSD/PJ)	
	Investment	O&M[a]
Refrigeration	63.8 [14,24,25]	8.7 [14,26]
Compressed air	63.9 [14,47]	12.8 [14,47,26]
Pumping	154.6 [14,29]	30.8 [14,29,26]
Fans	51.3 [14,24,25]	8.2 [14,26]
Other electric motors	51.2 [14,24,25]	11.2 [14,26]
Lighting	42.0 [48]	8.0 [48,26]
Diverse uses	36.9 [14,24,25]	5.7 [14,24,25,26]
Steam boilers	1711.0 [28,42,43]	100.4 [26,28,42,43]
Thermal fluid boilers	36.7 [28,42,43]	6.4 [26,28,42,43]
Furnaces & dryers	72.7 [28,42,43]	8.4 [26,28,42,43]

[a] The energy unit costs for electricity and fossil fuels namely: electricity, coke, fuel oil, NG, diesel and LPG are included in the O&M costs.

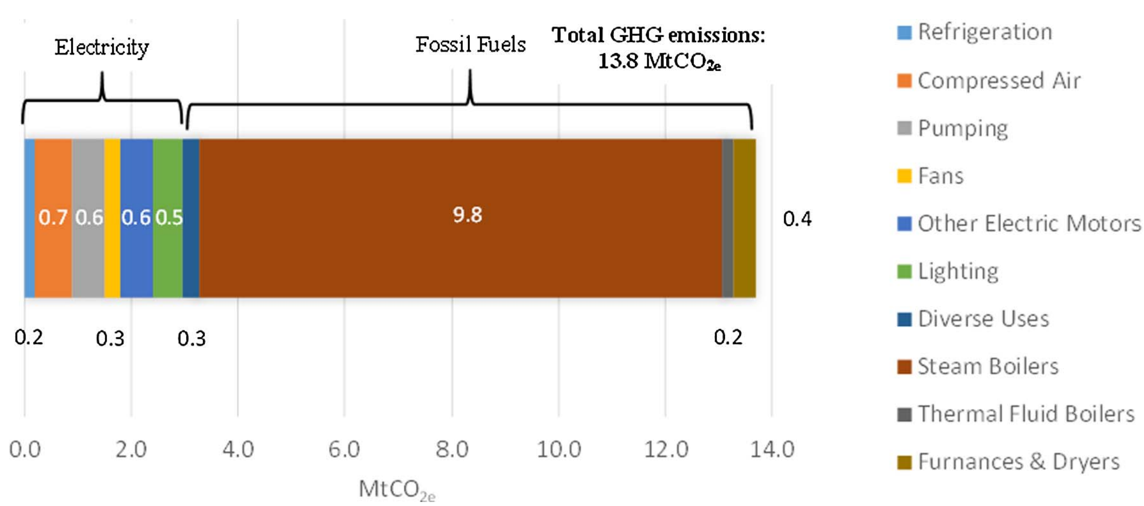

Fig. 3. GHG emissions by end-uses of energy in the MCI in 2014..
Source: Own estimates based on [7,13–15]

Table 2
Description and unit costs of the efficient use of energy and renewable energy sources options under the Low-carbon scenario 2015–2050.
Source: Own calculations based on the cited references.

Mitigation Measure	Measure ID[a]	Description	Unit Costs (MUSD/PJ)	
			Investment	O&M[b]
Automatized monitoring and control systems	EEU-AMCS	Automatized control and monitoring systems result in reductions in downtime, maintenance costs and processing time, which increases resource use, energy efficiency and emission control by reducing costs and increasing energy savings. Based on [19,20], an approximate reduction of 4% in total energy consumption is estimated for this measure	0.5 [19,20]	33.9 [21]
Efficient electric motors	EEU-EM	The increase in the efficiency of the motors coupled with a maintenance program can generate savings of between 2% and 30% in the total energy consumption associated with electric motors. Based on [14,22,23], a 16% saving in the consumption of E in electric motors is estimated	17.7 [14,22–26,30]	32.8 [14,22–26,30]
Efficient burners	EEU-EB	New burner designs improve fuel and air mix, making heat transfer more efficient. By increasing the efficiency of the burners by 2%, savings of approximately 2.5% are generated in both the costs and the use of fuels. Based on [27] a 13% reduction in FF consumption in boilers, ovens and dryers is considered for this measure	3.0 [28]	4.9 [28]
Improvement of pump systems	EEU-PS	The use of more efficient pumps coupled with a maintenance of the pumping system and an adequate design of pumps and pipes can generate savings of between 5% and 25% in the total energy consumption associated with pumping systems. According to [14,29,30] for the application of this measure is estimated a saving of 14% in E consumption in pumps	6.4 [14,22–25,29–31]	7.2 [14,22–25,29–31]
Use of adjustable speed devices	EEU-ASD	The energy savings of placing a ASD will depend on the final application of the electric motor, although these can vary between 7% and 60%. An additional saving of close to 2% in E consumption in electric motors is estimated for this measure according to [26,32]	18.3 [14,22–26,30]	32.9 [14,22–26,30]
Thermal process integration	EEU-TPI	In plants that have several demands for heating and cooling, the use of process integration techniques can significantly improve energy efficiency by joining hot and cold flows in a thermodynamic-optimal way. The typical savings identified at the site level are around 20% to 30% in energy consumption. Due to this measure, a reduction of around 9% in FF consumption in boilers, ovens and dryers is estimated, based on [33–35]	21.7 [33–37]	4.7 [33–37]
Improvement of steam generation and distribution systems	EEU-SGDS	The use of improved insulation, steam traps, leak repair, flue gas recovery and condensate return can mean savings of up to 30% in FF consumption. According to [23,27,38–42], a reduction of 13% in FF in steam boilers is estimated by the implementation of this measure	17.2 [38–44]	5.0 [38–44]
Improvement of compressed air systems	EEU-CAS	The elimination of leaks and unnecessary use of compressed air can mean savings of up to 18% in electricity consumption. Based on [30,45], for the application of this measure an approximate saving of 14% in the consumption of E related to the use of compressed air is estimated	28.2 [45–47]	10.5 [45–47]
Lighting controls	EEU-LC	Lighting controls can save between 10% and 20% of the energy consumption for lighting. For this measure is estimated a saving of 16% in E used in lighting, according to [23]	3.7 [48]	5.1 [48]
Combined heat and power	EEU-CHP	Savings determined by the use of CHP are around 75% in electric energy and 25% in fuel use. According to [26], the application of this measure estimates a reduction of around 8% in FF use and a saving of 23% in the use of E	19.6 [26]	34.7 [26]
Low-carbon electricity	RES-LCE	According to the Energy Transition Law, high energy consumers are obliged to verify that 5% of their energy consumption comes from renewable sources, with the option of purchasing it directly from Qualified Generators, which have the capacity to generate electricity through RES. Based on [49], this measure contemplates a 5% substitution in E from fossil fuels by E from photovoltaic, wind, geothermal and hydro energies	38.6 [50]	33.4 [50]
Solar photovoltaic energy	RES-PV	Photovoltaic systems with interconnection to the grid of the national electricity system can avoid E consumption from the grid between 10% and 12%. According to [26,51] this measure avoid 10% of E from the grid	50.2 [52]	37.1 [52]
Solar chilling	RES-SC	The contributions of solar refrigeration may represent 19% of E use for refrigeration. Based on [53], the application of this measure estimates a 13% substitution percentage for E consumption in refrigeration	64.7 [53]	12.1 [53]
Solar thermal energy (60–100 °C)	RES-STE-60	According to [33], the appropriate percentage in which energy consumption can be replaced by technologies that take advantage of the use of solar energy is 12%. The implementation of these measures estimates a reduction in the MCI FF consumption of 1% for low temperature applications (60–100 °C) and 10% for medium temperature applications (290–390 °C) in boilers, furnaces and dryers, according to [54–56]	73.7 [26,54]	11.7 [26,54]
Solar thermal energy (290–390 °C)	RES-STE-290		17.8 [55,56]	6.5 [55,56]

[a] EEU = Energy efficient use, RES = Renewable energy sources, E = Electricity.
[b] The energy unit costs for electricity and fossil fuels namely: electricity, coke, fuel oil, NG, diesel and LPG are included in the O&M costs.

Table 3
Percentage of the reduction potential in energy consumption by GHG mitigation measure and energy end-uses in the LC scenario.
Source: Own calculations.

Energy end-use	Refrigeration	Compressed air	Pumping	Fans	Other electric motors	Lighting	Diverse uses	Steam boilers	Thermal fluid boilers	Furnaces & dryers	Total
Mitigation measure											
EEU-AMCS	0.03	0.09	0.09	0.04	0.09	0.08	0.04	3.05	0.07	0.13	3.7
EEU-EM	1.33	4.37	4.16	1.97	4.16	0.00	0.00	0.00	0.00	0.00	16.0
EEU-EB	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.22	0.26	0.52	13.0
EEU-PS	0.00	0.00	14.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14.0
EEU-ASD	0.17	0.55	0.52	0.25	0.52	0.00	0.00	0.00	0.00	0.00	2.0
EEU-TPI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.46	0.18	0.36	9.0
EEU-SDGS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.22	0.26	0.52	13.0
EEU-CAS	0.00	14.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14.0
EEU-LC	0.00	0.00	0.00	0.00	0.00	16.00	0.00	0.00	0.00	0.00	16.0
EEU-CHP	1.38	4.60	4.37	2.07	4.37	3.91	2.30	7.52	0.16	0.32	31.0
RES-LCE	0.30	1.00	0.95	0.45	0.95	0.85	0.50	0.00	0.00	0.00	5.0
RES-PV	0.60	2.00	1.90	0.90	1.90	1.70	1.00	0.00	0.00	0.00	10.0
RES-SC	13.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.0
RES-STE 60–100 °C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.94	0.02	0.04	1.0
RES-STE 290–390 °C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.40	0.20	0.40	10.0

data obtained in the previous step, according to the methodology proposed by [63,64]. The calculation is made explicit in Eq. (7).

- Third, the penetration level of the 15 GHG mitigation measures in the MCI is established throughout the period, and was obtained after applying the Delphi Technique [16–18] to a group of experts from 19 companies of MCI.
- Fourth, the MCI's LC scenario is constructed in terms of its energy end-uses by calculating its energy consumption, corresponding GHG emissions and costs involved for the period 2015–2050.

2.3. Delphi technique

According to [16,57], this technique aims to obtain the highest degree of consensus possible among a group of experts on a specific topic through the application of questionnaires or surveys. In accordance with the Delphi methodology, surveys should be conducted in at least two rounds to generate consensus through feedback [17,58]. In this article, the design of the survey considered a market-driven case hypothesis to consult experts on the development of the 15 proposed mitigation measures for the MCI; that means that the development of such mitigation measures throughout the 2015–2050 will be driven by the market forces and not by the actions of the government [59]. With this hypothesis, two rounds of surveys were applied to experts from 19 MCI companies. The first was to determine the percentage of implementation (penetration level) of the 15 GHG mitigation measures proposed for this article, considering that in the reference year the development of these measures is null and from which the projection will be established on the level of penetration of said measures at intervals of 5 years until the year 2050. In the second round, according to the Delphi technique, the medians corresponding to the level of penetration of each mitigation measure in the 5-year, obtained in the first round, were presented to the group of experts and they were asked if the level of penetration should be *lower* (assigning a value of 1 to this option) or *greater/equal* (assigning a value of 2 for this option) to their respective medians. The consistency of the responses in this second round was determined by calculating the coefficient of variation for each assigned value for each measure in the 5-year interval. This coefficient of variation results from dividing the mean of the assigned values by its standard deviation. According to the Delphi technique, there is agreement among the experts if the result obtained for the coefficients of variation of each mitigation measure is less than 0.5 [18,60,61].

2.4. Economic calculation model

A net cost (NC) model is used to analyze the 15 mitigation measures by energy end-uses on the LC scenario in relation to the BAU scenario, based on the economic calculation model proposed by [26,62]. The total net cost was obtained by the following equation:

$$NC_{LC-BAU} = IC_{LC-BAU} + O\,\&\,MC_{LC-BAU} + EC_{LC-BAU} \tag{1}$$

where:

$IC_{LC\text{-}BAU}$ = Overall difference investment costs for all mitigation measures in the LC scenario in present value.
$O\&MC_{LC\text{-}BAU}$ = Overall difference costs of operation and maintenance for all mitigation measures in the LC scenario in present value.
$EC_{LC\text{-}BAU}$ = Overall difference costs of energy for all mitigation measures in the LC scenario in present value.

with:

$$IC_{LC-BAU} = \sum_{y=1}^{n}\sum_{i=1}^{Ms}\sum_{u_j}\frac{IC_{LC-BAU_{iu_jy}}}{(1+r)^y} \tag{2}$$

where:

$IC_{LC\text{-}BAUiujy}$ = Cumulative incremental investment costs in relation to the implementation of the mitigation measure i in the end-use u_j for any year y for all the period. This information is provided in Tables 1 and 2.
y = Year.
r = Discount rate (10%), and it is assumed that represents the actual cost of financing according to [26,62].
n = Analyzed period (35 years).
Ms = Number of alternative options in the LC scenario (15 mitigation measures).
u_j = Energy end-use j in the MCI (where u_1 = steam boilers, u_2 = thermal fluid boilers, u_3 = furnaces & dryers, u_4 = refrigeration, u_5 = compressed air, u_6 = pumping, u_7 = fans, u_8 = other electric motors, u_9 = lighting, u_{10} = diverse uses), see Tables 1 and 2;

where:

Table 4
Mitigation measures unit costs by energy end-uses (MUSD/PJ) in the Low-carbon scenario.
Source: Own Calculations.

Energy end-use	Refrigeration		Compressed air		Pumping		Fans		Other electric motors		Lighting		Diverse uses		Steam boilers		Thermal fluid boilers		Furnances & dryers		Total	
Mitigation measure	IC	O&M	IC	O&M	IC	O&M	IC	O&M	IC	O&M	IC	O&M	IC	O&M	IC	O&M	IC	O&M	IC	O&M	IC	O&M
EEU-AMCS	0.004	1.771	0.012	5.903	0.012	5.608	0.006	2.656	0.012	5.608	0.011	5.017	0.006	2.951	0.413	4.133	0.009	0.088	0.018	0.176	0.5	33.9
EEU-EM	1.469	5.903	4.832	8.954	4.607	8.537	2.182	4.044	4.607	8.537	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	17.7	32.8
EEU-EB	0.000	5.608	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.848	4.606	0.061	0.098	0.121	0.196	3.0	4.9
EEU-PS	0.000	2.656	0.000	0.000	6.420	7.200	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.4	7.2
EEU-ASD	1.523	5.608	5.010	8.995	4.776	8.576	2.262	4.062	4.776	8.576	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	18.3	32.9
EEU-TPI	0.000	5.017	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	20.410	4.379	0.434	0.093	0.869	0.186	21.7	4.7
EEU-SDGS	0.000	2.951	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	16.172	4.744	0.344	0.101	0.688	0.202	17.2	5.0
EEU-CAS	0.000	4.133	28.150	10.450	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	28.2	10.5
EEU-LC	0.000	0.088	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.680	5.130	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.7	5.1
EEU-CHP	0.137	0.176	0.470	5.921	0.450	5.625	0.215	2.664	0.450	5.625	0.411	5.033	0.235	2.960	16.175	4.754	0.352	0.102	0.685	0.202	19.6	34.7
RES-LCE	2.313	33.910	7.710	6.671	7.325	6.337	3.470	3.002	7.325	6.337	6.554	5.670	3.855	3.336	0.000	0.000	0.000	0.000	0.000	0.000	38.6	33.4
RES-PV	3.010	0.000	10.032	7.426	9.530	7.055	4.514	3.342	9.530	7.055	8.527	6.312	5.016	3.713	0.000	0.000	0.000	0.000	0.000	0.000	50.2	37.1
RES-SC	64.700	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	64.7	12.1
RES-STE 60–100 °C	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	69.297	10.972	1.474	0.233	2.949	0.467	73.7	11.7
RES-STE 290–390 °C	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	16.749	6.146	0.356	0.131	0.713	0.262	17.8	6.5

The energy unit costs for electricity and fossil fuels namely: electricity, coke, fuel oil, NG, diesel and LPG are included in the O&M costs.

$$u_j = 1 \ldots 10 \quad \text{for} \quad i = 1,10$$
$$u_j = 1,2,3,10 \quad \text{for} \quad i = 3,6,7,14,15$$
$$u_j = 5 \ldots 10 \quad \text{for} \quad i = 2$$
$$u_j = 6 \quad \text{for} \quad i = 4$$
$$u_j = 4 \ldots 10 \quad \text{for} \quad i = 5,11,12$$
$$u_j = 5 \quad \text{for} \quad i = 8$$
$$u_j = 9 \quad \text{for} \quad i = 9$$
$$u_j = 4 \quad \text{for} \quad i = 13 \tag{3}$$

$$O\,\&\,MC_{LC-BAU} = \sum_{y=1}^{n} \sum_{i=1}^{Ms} \sum_{u_j} \frac{O\,\&\,MC_{LC-BAU_{iujy}}}{(1+r)^y} \tag{4}$$

where:

$O\&MC_{LC\text{-}BAUiujy}$ = Cumulative incremental costs of operation and maintenance for the alternative option i in the end-use u_j accumulated in the year y for all the period. This information is provided in Table 1.

$$EC_{LC-BAU} = \sum_{y=1}^{n} \sum_{i=1}^{Ms} \sum_{u_j} \frac{EC_{LC-BAU_{iujy}}}{(1+r)^y} \tag{5}$$

where:

$EC_{LC\text{-}BAUiujy}$ = Annual avoided energy cost (FF and/or E) by mitigation measure i in the end-use u_j in the year y of period n, according to [26,62].

In order to calculate the mitigation cost for each mitigation measure the following calculation is used:

$$MC_{LC-BAUiu_j} = \frac{TC_{LC-BAUiuj}}{GHG_{LC-BAUiuj}} \tag{6}$$

where:

$TC_{LC\text{-}BAUiuj}$ = Total incremental costs of the mitigation measure i in the end-use u_j in the LC scenario in present value.

$$TC_{LC-BAUiu_j} = \sum_{y=1}^{n} \sum_{u_j} \left(\frac{IC_{LC-BAU_{iujy}}}{(1+r)^y} + \frac{O\,\&\,MC_{LC-BAU_{iujy}}}{(1+r)^y} + \frac{EC_{LC-BAU_{iujy}}}{(1+r)^y} \right) \tag{7}$$

See restrictions (3) for the energy end-use u_j for each mitigation measure i.

$GHG_{\ LC\text{-}BAUiuj}$ = Total reduction of greenhouse gases emissions by the implementation of the mitigation measure i in the corresponding end-uses u_j in the LC scenario.

$$GHG_{LC-BAUiuj} = direct\ \ GHG\ \ emissions + indirect\ \ GHG\ \ emissions \tag{8}$$

$$direct\ \ GHG\ \ emissions = \left(ES_{LC-BAUiuje} * \sum_{l=1}^{m} EF_{le} * GWP_{GHG_l} \right) \tag{9}$$

$ES_{LC\text{-}BAUiuje}$ = Avoided energy e by mitigation measure i in the LC scenario in the corresponding end-uses u_j of the BAU scenario.
EF_{le} = Emission factor of the source e of the greenhouse gas l.
l = CO_2, CH_4, NO_2.
e = Final use source (electricity, NG, diesel, coke, fuel oil, LPG).

$$indirect\ \ GHG\ \ emissions = (ES_{LC-BAUiuje} * EEF) \tag{10}$$

EEF = Average GHG emission factor of the SEN which value is 0.454 $kgCO_{2e}/kWh$ [65].

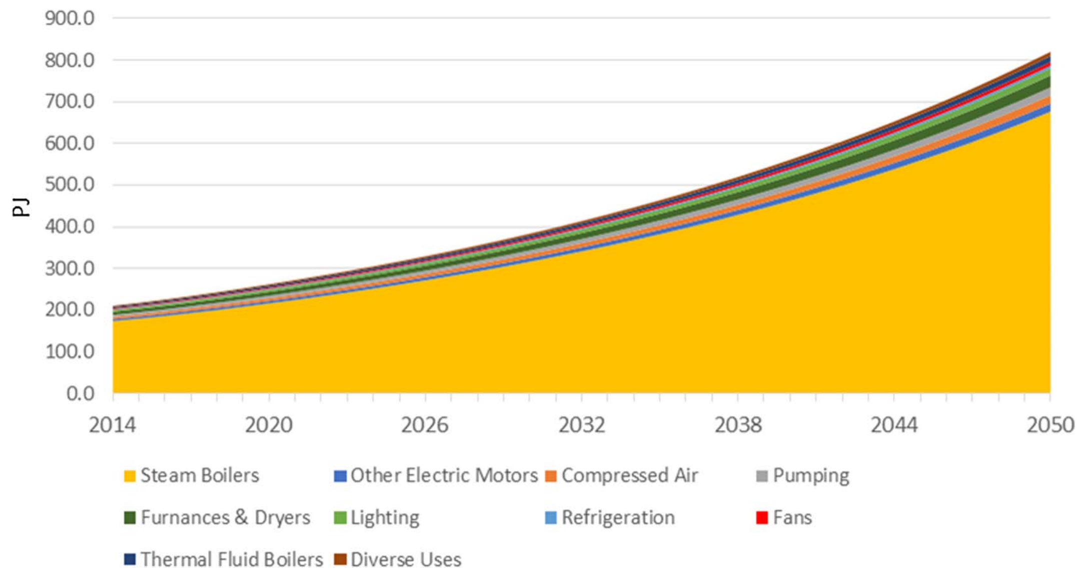

Fig. 4. Energy requirements by end use in the BAU scenario.
Source: Own data.

3. Results and discussion

3.1. BAU scenario

Fig. 4 shows that under BAU scenario conditions, the amount of energy required by the MCI is 820 PJ in 2050 which is 3.9 times higher than that required in 2014. The 87.8% of this energy comes from the burning of FF in steam boilers (82.5%), in boilers of thermal fluids (1.8%) and in furnaces and dryers (3.5%). While the remaining 12.2% comes from electricity consumption in lighting (2.1%), diverse uses (1.2%) and in refrigeration equipment (0.7%), compressed air (2.5%), pumping (2.3%), ventilation (1.1%) and other electric motors (2.3%). This scenario would consume an average of 474.9 PJ per year in the period 2015–2050, being 2.25 times greater than the energy consumption in the reference year.

According to this trend, Fig. 5 shows that GHG emissions in 2050 reach 53.1 $MtCO_{2e}$, being 390% higher than those emitted in 2014. Where 76.1% of these emissions come from the burning of FF in steam boilers, thermal fluid boilers, ovens and dryers. While the remaining 23.9% comes from electricity consumption in refrigeration, compressed air, pumping, fans, other electric motors, lighting and diverse uses.

3.2. Low-carbon scenario

Table 5 shows the potential for reduction in energy consumption and its respective GHG mitigation potential of the 15 mitigation measures proposed for the LC scenario, corresponding in 10 EEU measures, which consider reductions in both E as of FF; and in 5 measures of RES, which avoid the use of FF. The penetration level for each measure

Table 5
Energy consumption reduction and mitigation potential by EEU and RES measures for 2050.
Source: Own calculations.

Energy-efficient use			Renewable energy sources		
Measure ID	Energy consumption reduction (PJ)	GHG mitigation potential ($MtCO_{2e}$)	Measure ID	Avoided fossil fuels (PJ)	GHG mitigation potential ($MtCO_{2e}$)
EEU-AMCS	30.3	2.0	RES-LCE	5.0	0.6
EEU-EM	11.7	6.1	RES-PV	9.9	1.3
EEU-EB	93.6	0.8	RES-SC	0.7	0.1
EEU-PS	2.8	0.4	RES-STE-60	7.9	0.5
EEU-ASD	13.9	1.8	RES-STE-290	83.0	4.7
EEU-TPI	72.1	4.1			
EEU-SGDS	103.8	5.9			
EEU-CAS	2.8	0.4			
EEU-LC	2.5	0.3			
EEU-CHP	254.8	15.9			
Total	588.3	37.7	Total	106.5	7.2

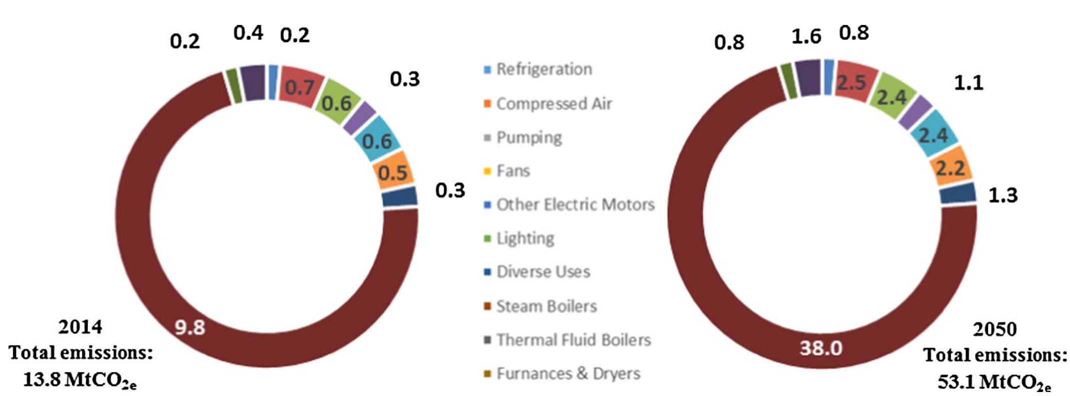

Fig. 5. GHG emissions in BAU scenario by final use of energy between years 2014 and 2050.
Source: Own data.

Table 6
Results of the evolution of the penetration level of the mitigation measures, 2015–2050.
Source: Own estimations based on the Delphi Technique application to experts of the MCI.

GHG mitigation measure	2015	2020	2025	2030	2035	2040	2045	2050	Coefficient of variation
EEU-AMCS	18%	70%	95%	100%	100%	100%	100%	100%	0.2
EEU-EM & EEU-EB	16%	70%	85%	90%	100%	100%	100%	100%	0.2
EEU-PS	15%	75%	79%	100%	100%	100%	100%	100%	0.1
EEU-ASD	15%	75%	79%	100%	100%	100%	100%	100%	0.3
EEU-TPI	10%	46%	50%	56%	70%	70%	80%	100%	0.2
EEU-SDGS	23%	90%	95%	95%	100%	100%	100%	100%	0.3
EEU-CAS	23%	95%	98%	100%	100%	100%	100%	100%	0.2
EEU-LC	6%	70%	85%	90%	100%	100%	100%	100%	0.3
EEU-CHP	13%	36%	51%	70%	77%	79%	83%	90%	0.2
RES-LCE	8%	35%	55%	93%	96%	100%	100%	100%	0.2
RES-PV	5%	41%	60%	70%	80%	90%	90%	91%	0.3
RES-SC	5%	23%	41%	56%	67%	73%	76%	81%	0.2
RES-STE-60	4%	38%	56%	76%	79%	87%	91%	100%	0.3
RES-STE-290	6%	22%	35%	46%	59%	64%	65%	70%	0.2

determines the impact of these EEU and RES measures on the total MCI energy.

Table 6 shows the results in the application of the Delphi technique involving the participation of 19 experts from companies in the MCI in terms of the penetration level of the 15 mitigation measures proposed in this study. Likewise, it is shown that the variation coefficients for the mitigation measures analyzed have values between 0.1 and 0.3, depending on the mitigation measure, with an approximate average of 0.2 for all measures. Since the coefficients of variation are less than 0.5, this indicates that there is consistency in the responses, which means, according to the Delphi technique, that there is consensus among experts on the penetration level of the mitigation measures in the period 2015–2050.

Table 7 shows the reduction in energy consumption per mitigation measure in the period 2015–2050, where the EEU-CHP and EEU-SDGS measures are the ones with the highest reduction percentage, with 33.6% and 18.5%, respectively. In addition, the implementation of the LC scenario means a cumulative reduction in the total energy consumption of 10,777 PJ in the period 2015–2050, which compared with the accumulated energy consumption in the BAU scenario of 16,613 PJ, represents an average reduction of 1.2% per year. As well this table shows, among parenthesis, the values of the avoided emissions by mitigation measure in the same period. It is also shown that the measures indicated above that reduce energy the most, namely EEU-CHP and EEU-SDGS, are those with the higher emissions reduction share, reaching 52.1% of the total accumulated reduction. Finally, it is shown that by the year 2050 the accumulated total avoided emissions are 697 $MtCO_{2e}$, which represent around 65% of the cumulated total emissions of the BAU scenario.

While on the RES side, the use of solar energy has the highest percentage of emissions avoided in measures that replace direct emission generating equipment such as RES-STE in the range of 60–100 °C and 290–390 °C, which together represent 8.2%, while those measures that prevent the generation of indirect emissions such as RES-PV and RES-SC represent 9.4% of the total accumulated.

According to Fig. 6, in the last year of the period, the reduction in energy consumption derived from the application of the 15 mitigation measures is 643.5 PJ, which represents 78.5% of the energy consumption of the BAU scenario from the same year. Of this reduction, the measures related to the efficient use of energy represent 87.5% while the measures related to renewable energy sources represent 12.5%.

In addition, the application of the low carbon scenario significantly impacts the generation structure of GHG emissions between the reference year and the final year for the MCI's energy end-uses (Fig. 7). By direct GHG emissions generation, steam boilers reduce their participation rate from 72% to 58.8%, fluid boilers from 1.5% to 1.2% and furnaces & heaters from 3.1% to 2.5%. On the other hand, energy end-uses related to indirect GHG emissions show increases in their share in emissions generation, since the consumption of electricity in the MCI is not predominant, which decrease the reduction potential of mitigation

Table 7
Energy reduction (PJ) and avoided GHG emissions ($MtCO_{2e}$) by mitigation measure in the LC scenario 2015–2050.
Source: own calculations.

GHG mitigation measure	2015	2020	2025	2030	2035	2040	2045	2050	Accumulated
EEU-AMCS	1.4(0.1)	6.8(0.5)	11.1(0.7)	14.2(0.9)	17.2(1.1)	20.7(1.4)	25.1(1.7)	30.3(2.0)	572.6(38.1)
EEU-EM	1.0(0.1)	5.2(0.3)	7.6(0.5)	9.8(0.6)	13.1(0.8)	15.9(1.0)	19.2(1.2)	23.2(1.5)	427.1(27.4)
EEU-EB	3.5(0.2)	18.4(1.2)	27.0(1.7)	34.6(2.2)	46.5(3.0)	56.2(3.6)	67.9(4.4)	82.1(5.3)	1511.7(97.0)
EEU-PS	0.1(0.0)	0.7(0.1)	0.9(0.1)	1.3(0.2)	1.6(0.2)	1.9(0.2)	2.3(0.3)	2.8(0.4)	52.6(6.7)
EEU-ASD	0.6(0.1)	3.3(0.4)	4.3(0.5)	6.5(0.8)	7.9(0.1)	9.5(1.2)	11.5(1.5)	13.9(1.8)	258.6(32.7)
EEU-TPI	1.9(0.1)	10.6(0.6)	13.9(0.8)	18.9(1.1)	28.5(1.6)	34.5(1.9)	47.7(2.7)	72.1(4.1)	989.3(55.8)
EEU-SDGS	6.2(0.4)	29.9(1.7)	38.2(2.2)	46.1(2.6)	58.7(3.3)	71.0(4.0)	85.8(4.8)	103.8(5.9)	1989.6(112.2)
EEU-CAS	0.2(0.0)	0.8(0.1)	1.1(0.1)	1.3(0.2)	1.6(0.2)	1.9(0.2)	2.3(0.3)	2.8(0.4)	54.1(6.8)
EEU-LC	0.1(0.0)	0.6(0.1)	0.8(0.1)	1.1(0.1)	1.4(0.2)	1.7(0.2)	2.1(0.3)	2.5(0.3)	46.4(5.9)
EEU-CHP	5.1(0.3)	29.4(1.8)	50.3(3.1)	83.5(5.2)	111.0(6.9)	137.7(8.6)	174.9(10.9)	229.3(14.3)	3622.5(226.4)
RES-LCE	0.1(0.0)	0.6(0.1)	1.1(0.1)	2.2(0.3)	2.7(0.3)	3.4(0.4)	4.1(0.5)	5.0(0.6)	84.5(10.7)
RES-PV	0.1(0.0)	1.3(0.2)	2.3(0.3)	3.3(0.4)	4.5(0.6)	6.1(0.8)	7.4(0.9)	9.1(1.1)	150.7(19.1)
RES-SC	0.0(0.0)	0.1(0.0)	0.1(0.0)	0.2(0.0)	0.3(0.0)	0.4(0.0)	0.5(0.1)	0.6(0.1)	8.9(1.1)
RES-STE-60	0.1(0.0)	1.0(0.1)	1.7(0.1)	2.8(0.2)	3.5(0.2)	4.7(0.3)	6.0(0.3)	7.9(0.4)	122.0(6.9)
RES-STE-290	0.7(0.0)	5.8(0.3)	11.2(0.6)	17.9(1.0)	27.7(1.6)	36.3(2.0)	44.6(2.5)	58.1(3.3)	886.8(50.0)
Total	21.1(1.3)	114.4(7.4)	171.7(11.1)	243.5(15.8)	326.2(21.1)	402.0(26.0)	501.4(32.4)	643.5(41.4)	10773.0(696.7)

Note: (1) These results were obtained using the information provided in Tables 3 and 6 according to Appendix A. (2) The values of the avoided emissions appear in parentheses and were calculated in a similar way according to Appendix A.

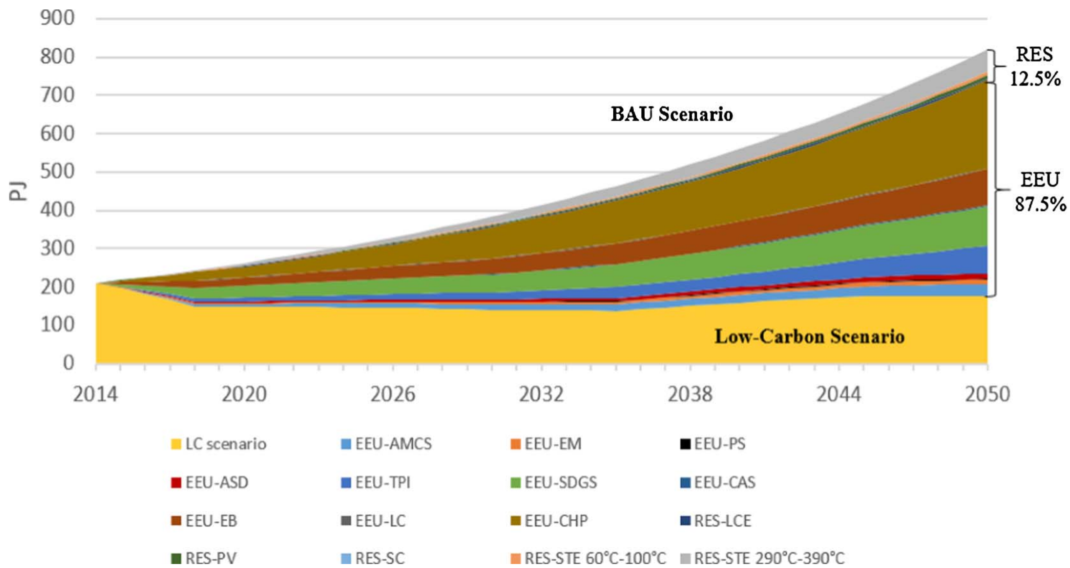

Fig. 6. Contribution to reduce the energy consumption in the Low-Carbon scenario by mitigation measure.
Source: Own calculations.

measures associated with this type of emissions. However, cumulatively, the share of energy end-uses related to indirect emissions increases annually at a rate of 1.4%, which is much lower than that established for the BAU scenario.

3.3. Net cost analysis

The results of the mitigation cost analysis for each measure mentioned in the previous section are shown in Fig. 8. The Y axis represents the mitigation cost and the X axis represents the accumulated GHG emissions in the analysis derived from the implementation of each mitigation measure and classified from a minor to a higher cost. As can be seen most mitigation measures involve negative costs, which means that economic benefits are obtained when applied. Of all the measures the EEU-CHP is the measure with the greatest economic benefit and a significant reduction of emissions. Followed by EEU-SDGS and EEU-TPI, both with a significant reduction of GHG emissions and economic benefit. Regarding RES measures, RES-STE 60–290 °C is the only measure that results in an economic benefit, albeit with a low volume of GHG emission reduction. However, considering that in the region the carbon price is between 12 and 20 USD/tCO_{2e} for Canada and 10–11 USD/tCO_{2e} in the United States [66] and that companies in the petrochemical sector such as Exxon Mobil (United States) and Imperial Oil (Canada) have established an internal carbon price of around 70 USD/tCO_{2e} [67], the rest of the alternatives related to renewable energy considered in the LC scenario, have a very competitive cost, as is the case of Solar Photovoltaic Energy with a cost of 5.1 USD/tCO_{2e}, while the rest of the solar alternatives have acceptable costs under 25 USD/tCO_{2e}.

Table 8 shows that the application of the LC scenario involves total investment costs of 13,200 MUSD and O&M costs of 898 MUSD over the 35 years of the period of study. However, this scenario results in total benefits of 21,334 MUSD, related with energy savings, generating a net economic benefit of 7,236 MUSD. This means that a no cost LC scenario is created for the MCI.

According to Table 8, it can be estimated, in a global way, that the average investment cost to mitigate 1 ton of CO_{2e} is equal to 18.9 USD, which is similar to the value of 17.1 USD/tCO_{2e} from the reference [6], obtained for its maximum decarbonization scenario of the study to mitigate CO_{2e} in the United Kingdom's chemical industry with alternatives similar to those in this article, except for the use of biomass and carbon capture & storage, and in which a cumulative emission reduction of 88% is achieved in the period 2013–2050. While in our article an accumulated reduction of 65% is achieved in the period 2015–2050. As can be seen, our results can be compared favorably with those obtained by other similar studies.

4. Conclusions

The portfolio of GHG mitigation measures discussed in this article

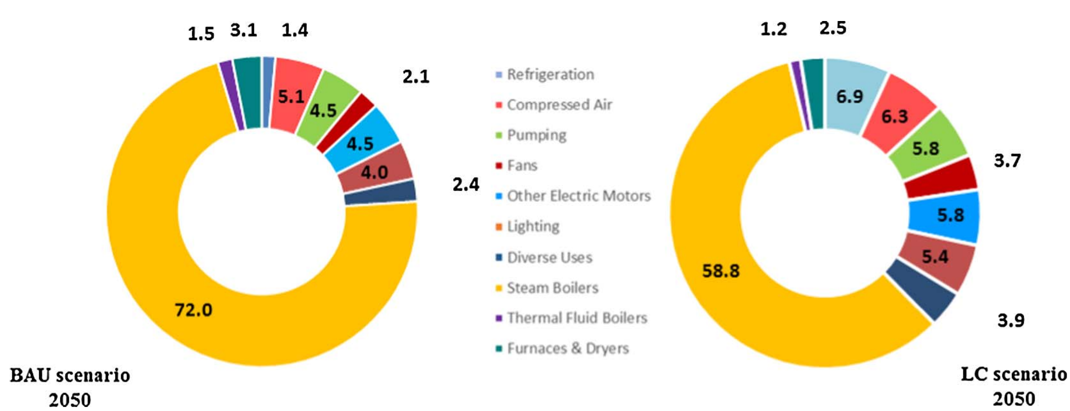

Fig. 7. Participation change of GHG emissions by energy end-use in 2050 between BAU and LC scenarios.
Source: Own calculations.

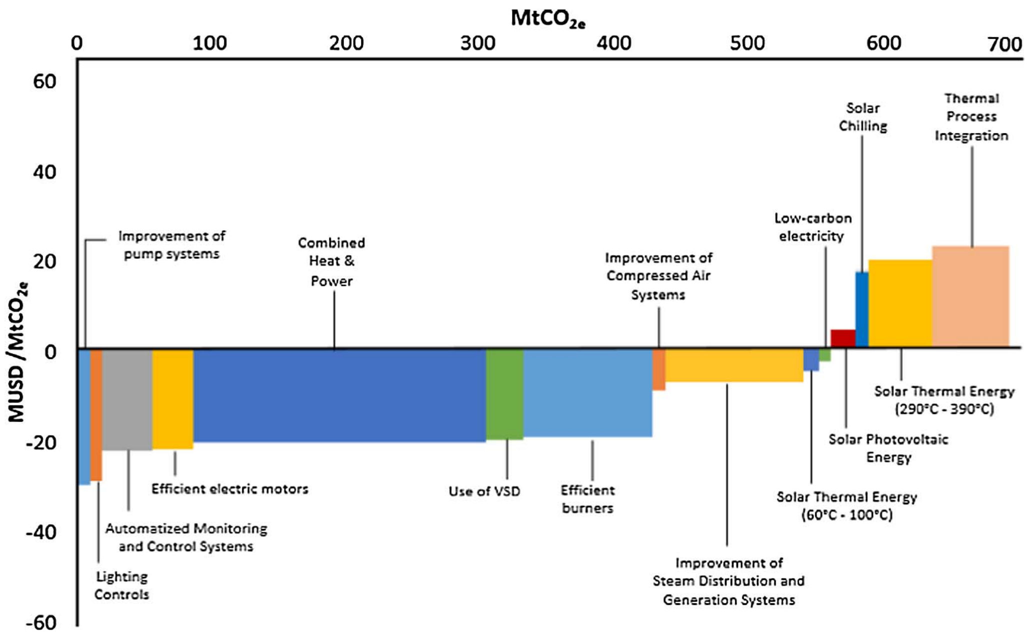

Fig. 8. Mitigation cost curve for EEU and RES mitigation measures in the Low-Carbon scenario for the MCI.
Source: Own calculations.

leads to a considerable change in the structure of the MCI's energy end-uses towards to the end of the 2015–2050 period, which in turn results in cumulative GHG emissions reduction potential equal to 696.7 $MtCO_{2e}$ (87.8 $MtCO_{2e}$ related to RES and 608.9 to EEU) representing a reduction of 65% with respect to emissions accumulated in the BAU scenario. Nevertheless, the replacement of 14% of conventional electricity by clean electricity, with 5% of low carbon electricity and 9% of solar distributed generation in the LC scenario, expresses a certain, but still a low decarbonization of the MCI's electricity consumption that fails into reduce the proportion of the indirect emissions and the direct emissions from the thermal energy consumption of the MCI in the LC scenario. The final results show that at the end of the period, GHG emissions are approximately of 11.5 $MtCO_{2e}$, which is 17% lower than the reference year 2014. In addition, all the mitigation measures considered for the LC scenario together generated total benefits of 21,334 MUSD, in contrast to the total costs of 14,098 MUSD, resulting in a LC scenario with no cost to the MCI and a net economic benefit of 7,236 MUSD in the analyzed period. Therefore, a transition to a low carbon Mexican Chemical Industry is technically and economically feasible, having as main challenge the additional investment of 13,200 MUSD required for the implementation of this scenario.

Acknowledgments

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Appendix A. Energy reduction and avoided GHG emissions calculation model for the low-carbon scenario

The results for the energy reduction for each measure in the period 2015–2050 for the LC scenario, shown in Table 7, were obtained according to the following equation:

Table 8
Net cost, saved emissions and mitigation cost by mitigation measure in the Low-Carbon scenario.
Source: Own calculations.

Mitigation alternative	Investment cost (MUSD)	O&M cost (MUSD)	Energy cost (MUSD)	Net cost (MUSD)	Saved emissions ($MtCO_{2e}$)	Mitigation cost ($MUSD/MtCO_{2e}$)
EEU-AMCS	3.8	1.0	−937.1	−932.3	38.1	−24.5
EEU-EM	252.5	47.3	−890.3	−590.5	27.4	−21.6
EEU-EB	160.8	30.6	−2019.8	−1828.4	97	−18.8
EEU-PS	17.9	4.5	−218.6	−196.2	6.7	−29.3
EEU-ASD	385.8	72.0	−1075	−617.2	32.7	−18.9
EEU-TPI	2314.1	41.0	−1041.3	1313.8	55.8	23.5
EEU-SDGS	1771.2	16.2	−2527.8	−740.4	112.2	−6.6
EEU-CAS	160.9	30.6	−247.6	−56.1	6.8	−8.3
EEU-LC	16.6	3.2	−188.5	−168.7	5.9	−28.6
EEU-CHP	5874.1	328.8	−10713.5	−4510.6	226.4	−19.9
RES-LCE	7.6	0.8	−30.2	−21.8	10.7	−2.0
RES-PV	529.0	100.6	−533.0	96.6	19.1	5.1
RES-SC	41.0	7.8	−29.0	19.8	1.1	18.0
RES-STE-60	20.2	3.8	−52.3	−28.3	6.9	−4.1
RES-STE-290	1644.5	209.5	−830.0	1024.0	50.0	20.5
Total	13200	897.7	−21334	−7236.3	696.7	−10.4

$$ES_{LCi} = \sum_{y=1}^{n} \left[\left(\sum_{uj=1}^{uj=10} C_{BAUujy} * P_{iuj} \right) * L_{iy} \right]$$

where:

ES_{LCi} = Cumulative energy consumption reduction of the GHG mitigation measure i in the end-uses of energy u_j for the year y in the period 2015–2050 on the LC scenario.
C_{BAUujy} = Energy consumption of the end-use of energy uj in the year y on the BAU scenario in the period 2015–2050.
P_{iuj} = Energy consumption reduction potential of the GHG mitigation measure i in the end-use of energy uj, see Table 3.
L_{iy} = Penetration level of the GHG mitigation measure i for the year y in the period 2015–2050, see Table 6.

With:

y = year;
n = analyzed period (35 years);
u_j = energy end-use j in the MCI (where u_1 = steam boilers, u_2 = thermal fluid boilers, u_3 = furnaces & dryers, u_4 = refrigeration, u_5 = compressed air, u_6 = pumping, u_7 = fans, u_8 = other electric motors, u_9 = lighting, u_{10} = diverse uses), see Tables 1 and 2, and restrictions (3) for the energy end-use uj for each mitigation measure i;
i = GHG mitigation measure in the LC scenario (15 mitigation measures).

Below is an example for the calculation of the total energy consumption reduction of the mitigation measures, ES_{LCiujy}, in the year 2050, according to the above equation:

(a) Data:
i = 1 = EEU-AMCS
y = 2050
$C_{BAUuj2050}$ = u_1 = steam boilers (676.4 PJ), u_2 = thermal fluid boilers (14.4 PJ), u_3 = furnaces & dryers (28.8 PJ), u_4 = refrigeration (6.0 PJ), u_5 = compressed air (20.1 PJ), u_6 = pumping (19.1 PJ), u_7 = fans (9.0 PJ), u_8 = other electric motors (19.1 PJ), u_9 = lighting (17.1 PJ), u_{10} = diverse uses (10.0 PJ) P_{1uj} = $u1$ = steam boilers (3.05%), $u2$ = thermal fluid boilers (0.07%), $u3$ = furnaces & dryers (0.13%), $u4$ = refrigeration (0.03%), $u5$ = compressed air (0.09%), $u6$ = pumping (0.09%), $u7$ = fans (0.04%), $u8$ = other electric motors (0.09%), $u9$ = lighting (0.08%), $u10$ = diverse uses (0.04%) $L_{1_{2050}}$ = 100%
(b) Result:

$$ES_{LCiu2050} = [\left(C_{BAUu1_{2050}} + \ldots + C_{BAUu10_{2050}}\right) * \left(P_{1u1} + \ldots + P_{1u10}\right)] * L_{1_{2050}} ES_{LCiu2050} = 820*0.037*1 = 30.3 \text{ PJ}$$

The total energy consumption reduction by the application of the mitigation measure i = 1 = EEU-AMCS in the year 2050 is ***30.3 PJ***

The calculation of the avoided GHG emissions it is carried out in the same way as for the calculation of the reduction in energy consumption, having previously calculated the emissions generated by the energy consumption according to Eq. (8) of the section *Economic calculation model.*

Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.applthermaleng.2018.02.076.

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